Automated Flight Planning for SOFIA

Jeremy Frank
Elif Kurklu (QSS)
NASA Ames Research Center
Moffett Field, CA

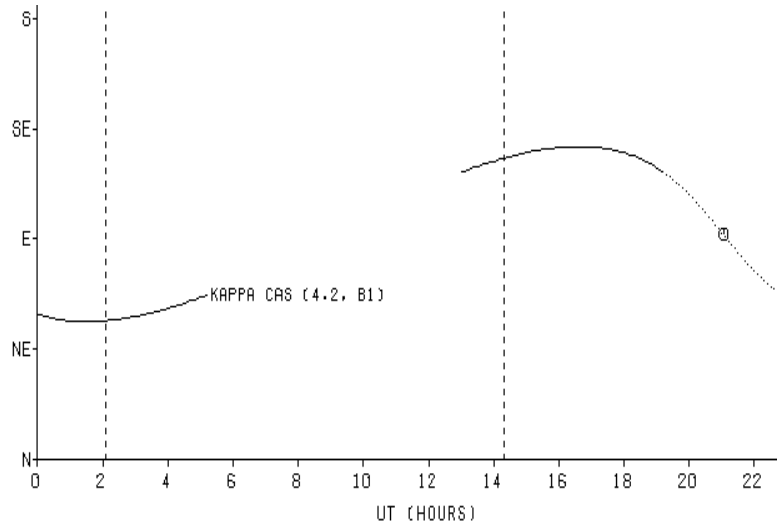
Church of St. Alexander Nevski, Sofia, Bulgaria

SOFIA's Choice

- The Observatory
  - 747SP aircraft with a 2.7m infrared telescope
  - Telescope elevates 20-60 degrees vertical, no horiz.
  - Flights of 6-8 hours, originate and terminate at Moffett
  - 3-4 instruments initially, more later
- The General Investigator Program
  - Astronomers request individual observations
  - Estimated 70 flights/year, 5-15 observations/flight

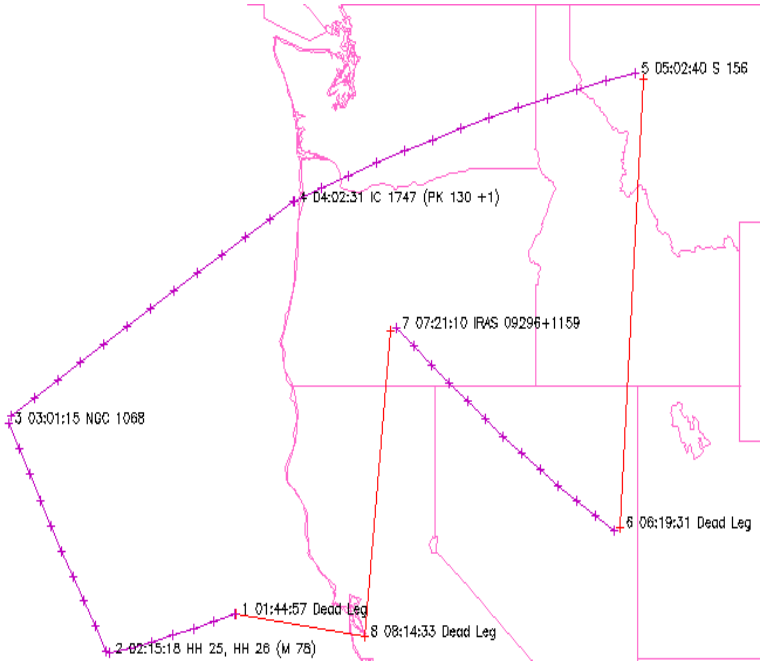
Constraints

- Aircraft constraints
  - Elevation limits
  - Restricted horizontal telescope motion
  - Flight duration, altitude profile, takeoff/landing sites
- Astronomical constraints
  - Object visibility



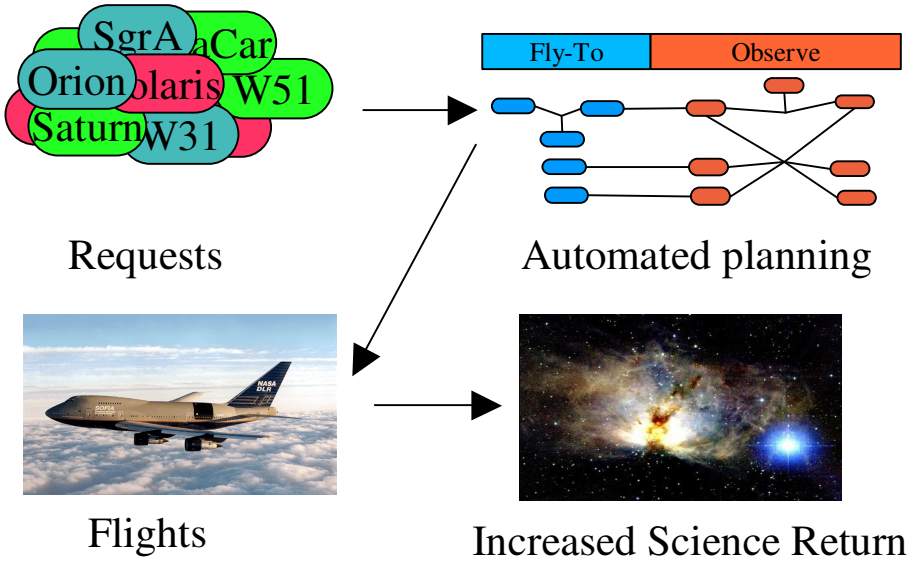
The Flight Planning Problem

- Given:
  - Takeoff time ranges, flight duration
  - Observation requests (object, duration, time, importance)
- Want:
  - Takeoff and landing time
  - Set of observation requests scheduled
  - Times of observations
  - Sequence of flight legs and dead legs



Technical Approach

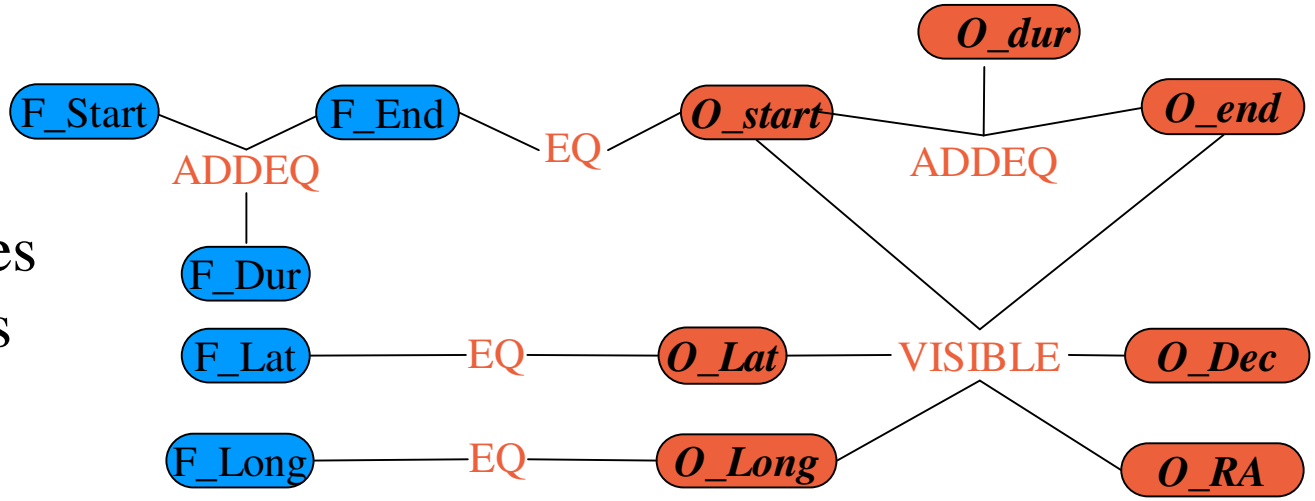
- Representation
  - Constraint-Based Interval Planning
- Planning algorithms
  - Stochastic Search with Forward Planning
  - Family of variable ordering heuristics



Constraint-Based Interval Planning

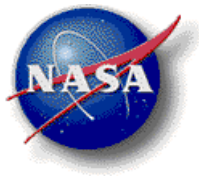
Activities

Induced Variables and Constraints



Modeling the Flight Planning Problem

- Request format
  - RA, Dec, Duration and Priority of observation
- Initial assumptions
  - Plan for a single flight
  - Unrestricted airspace
  - No altitude, winds or water vapor constraints
  - Flight duration constraint (fuel consumption is ignored)
- Principal Intervals (i.e. Activities)
  - Takeoff, Landing, Turns, Observing Legs, Dead (Non-Observing) Legs
- Principal constraints
  - Object visibility constraint
    - Position, elevation restrictions, object coordinates
  - Object tracking constraints
    - Air speed, flight direction, object coordinates
  - Simplified turns



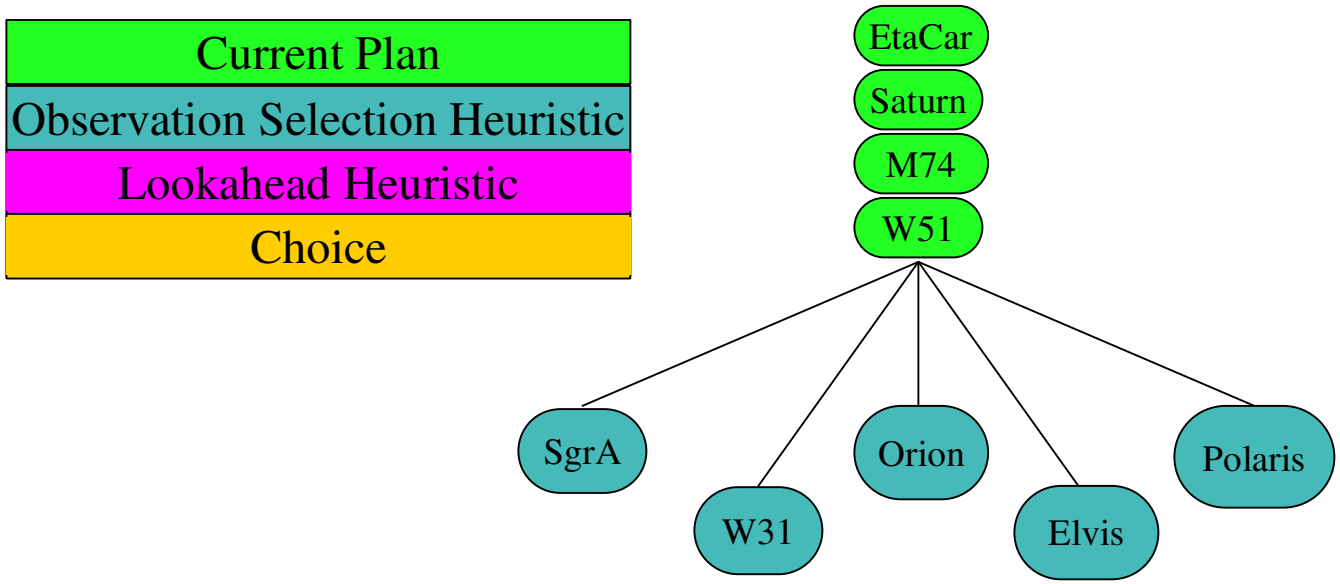
Forward Search Algorithm

```
Randomly choose a takeoff time
While not done
    for each observation
        if observation can be performed in remaining time
            evaluate the observation
        end if
    end for
    if no observations visible in time remaining
        construct dead leg home
    else
        randomly choose one of the observations
        insert the observation
    end if
end while
```

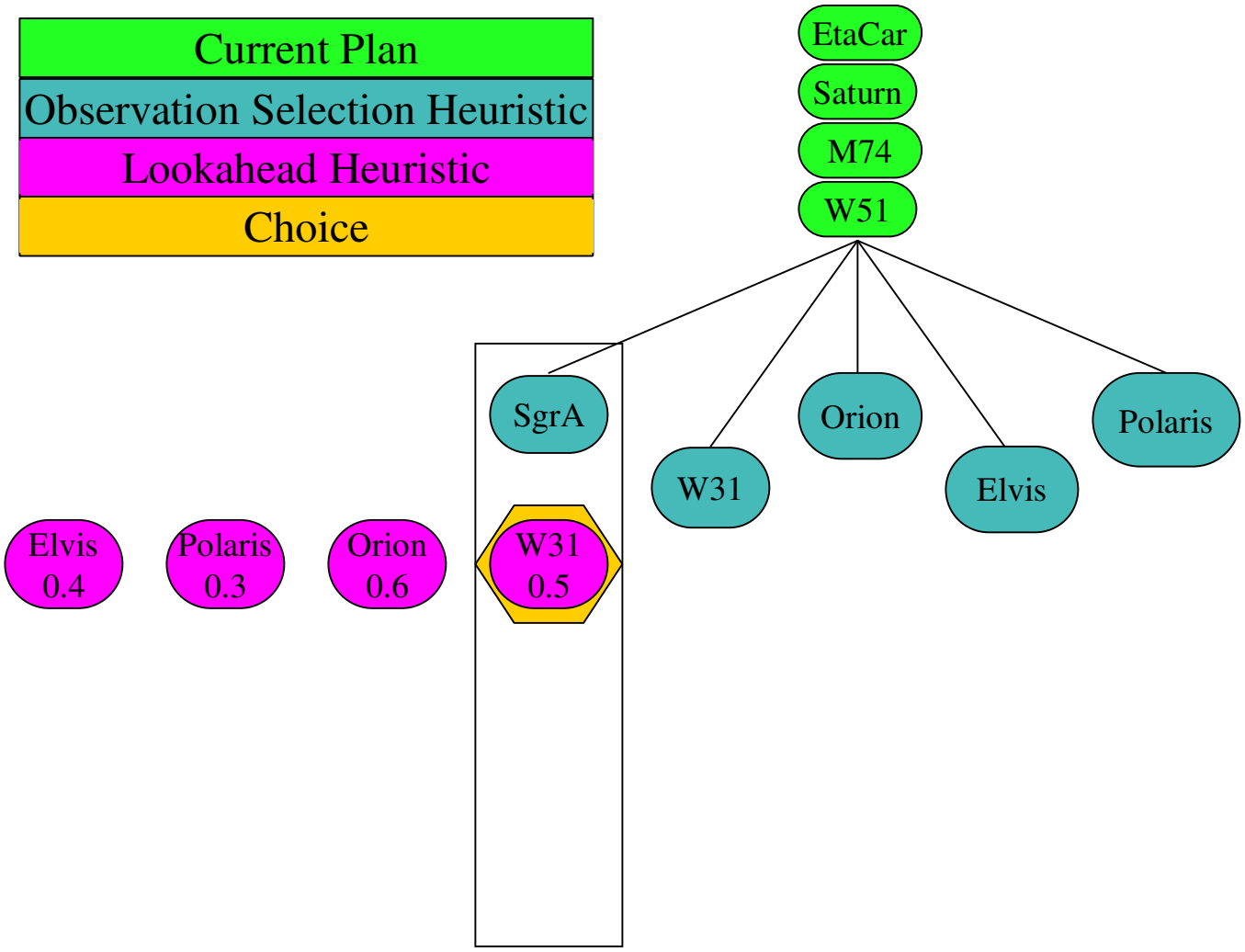
Evaluating an Observation

- Observation selection heuristic
  - Weighted sum of features of plan constructed by lookahead
    - R: Summed priority of observations in plan
    - E: Observation efficiency of plan
- Lookahead heuristic
  - Weighted sum of features of next observation
    - P: Observation priority
    - D: Observation efficiency (observation duration/flight time)
    - T: Amount of turning required
    - H: Time to destination airport after observation
- Noise (used in both)
  - With probability p, greedily select best candidate
  - Otherwise, sample using heuristic as probability mass

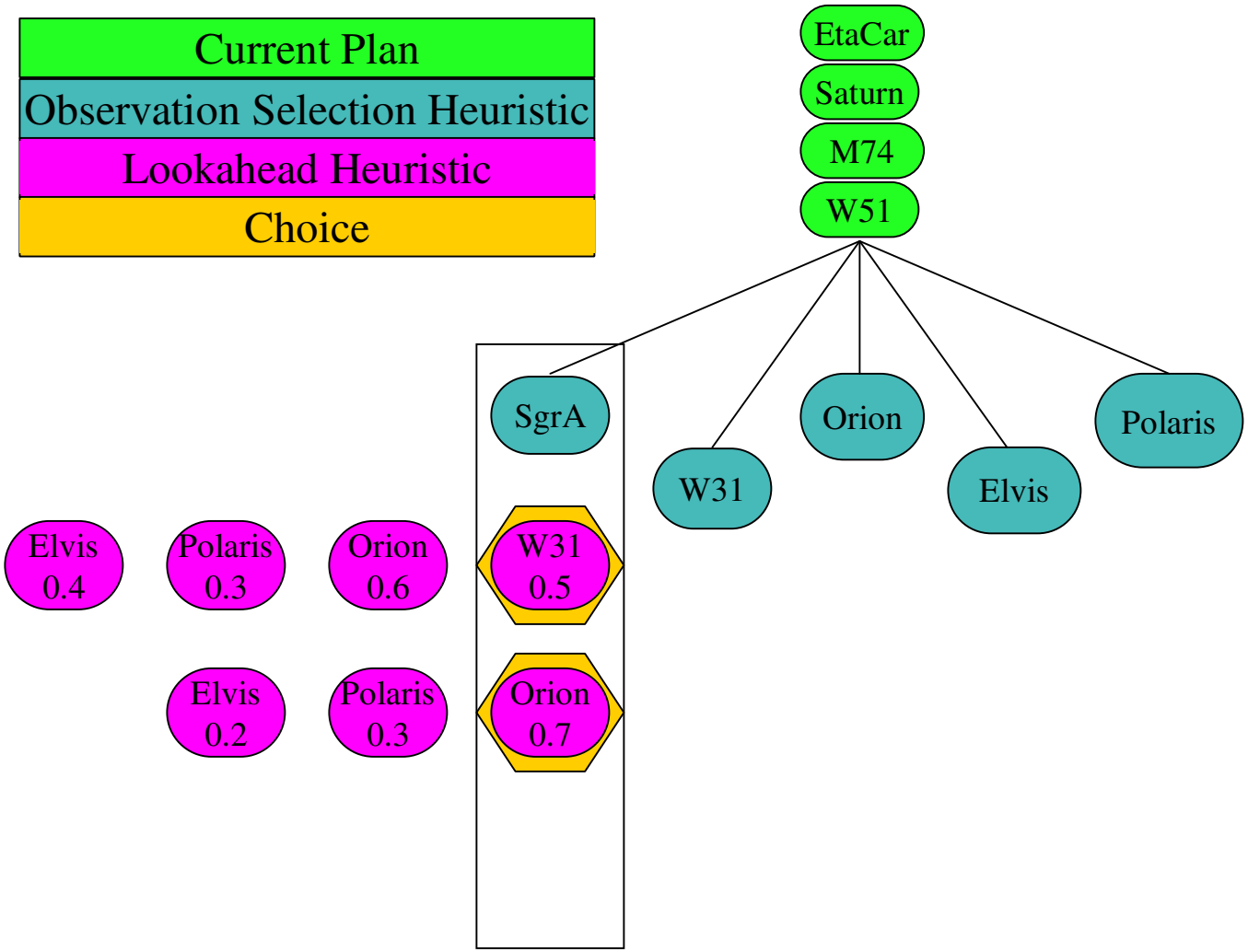
Forward Search with Lookahead



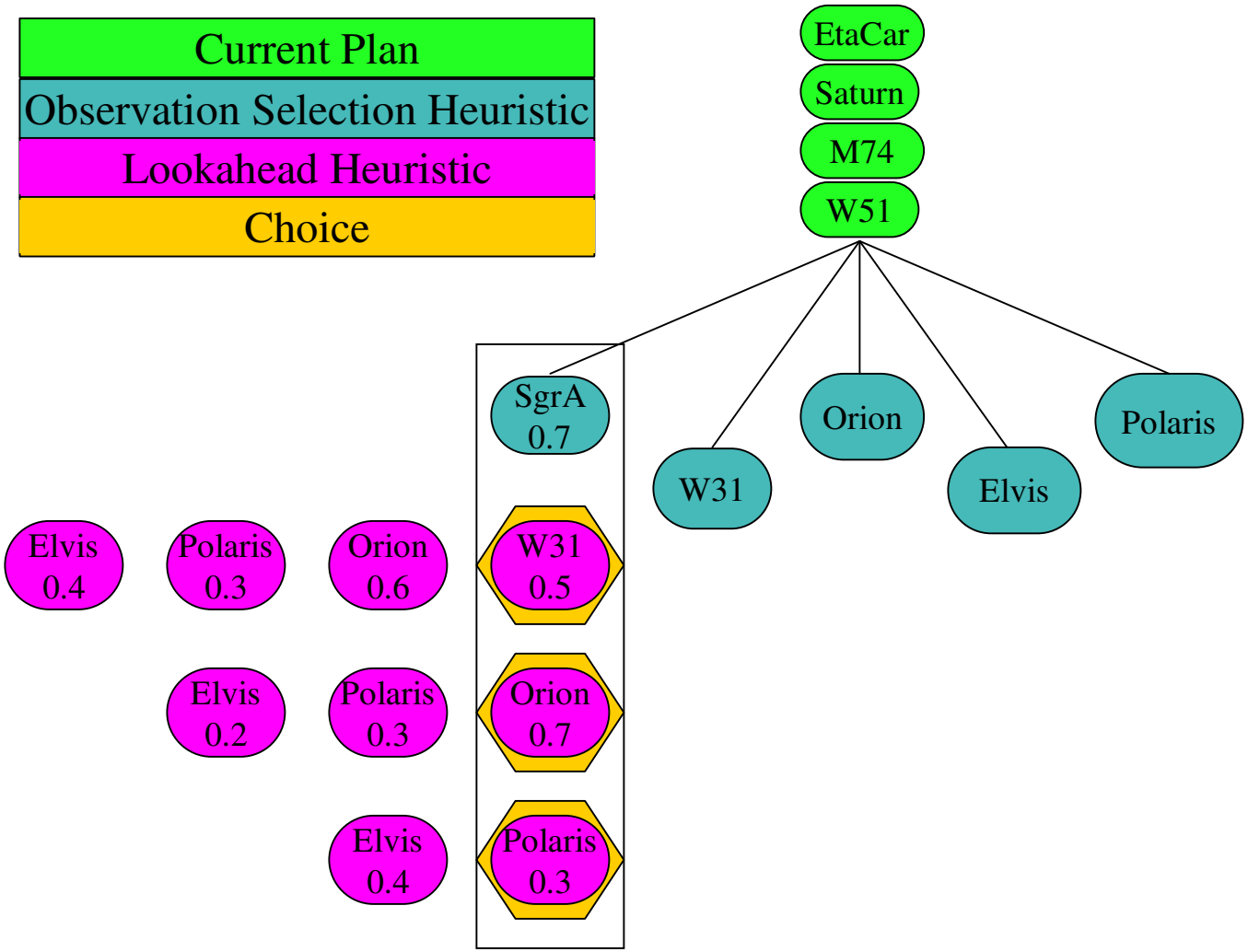
Forward Search with Lookahead



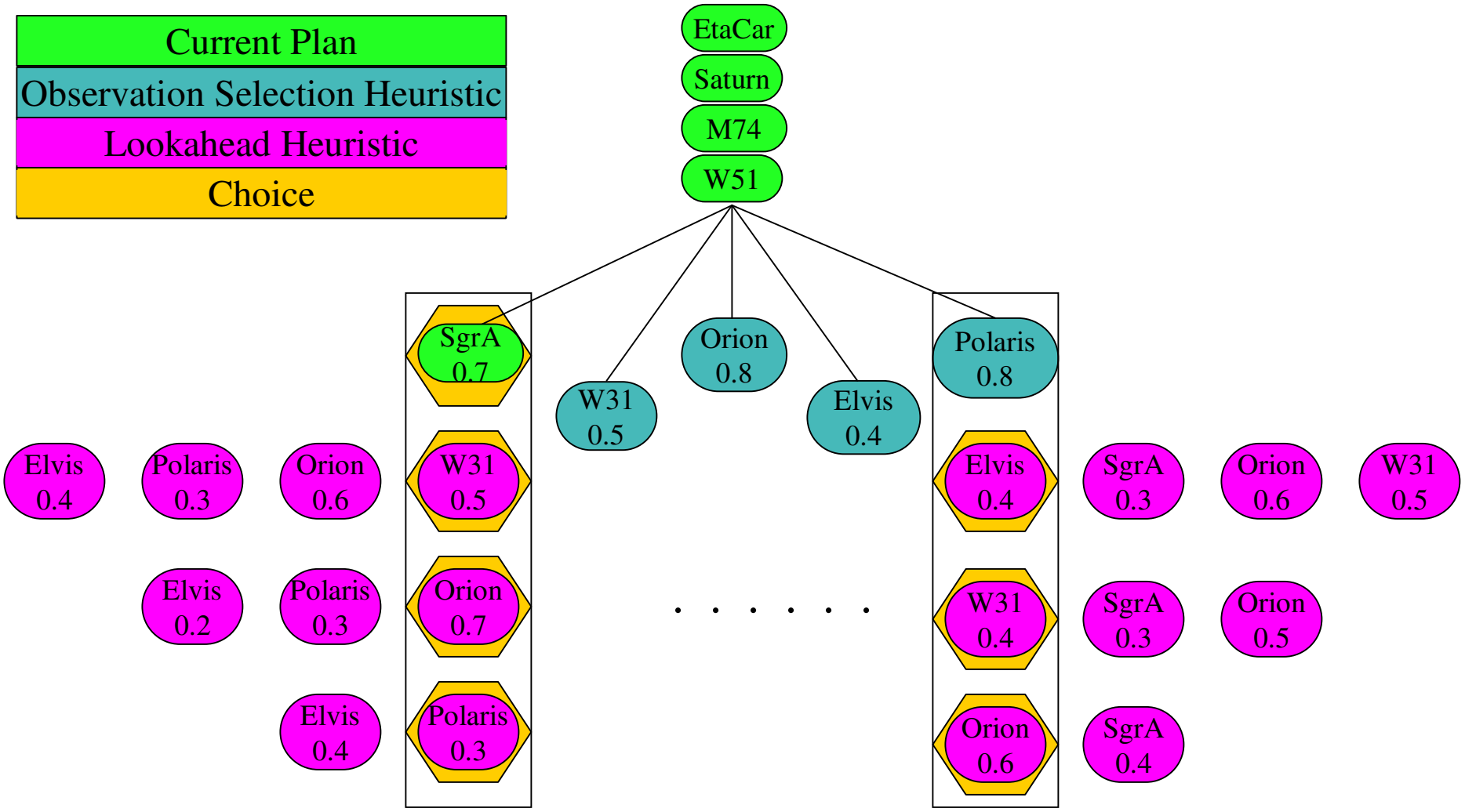
Forward Search with Lookahead



Forward Search with Lookahead

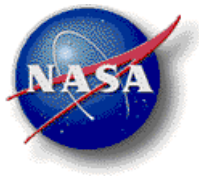


Forward Search with Lookahead



Additional Forward Search Details

- Feasibility of observations
  - Limit candidate dead legs to enable
  - Headings limited to 7.5 degree increments
  - 4 hour dead leg limit, 1 minute increments
- Ensure that dead leg home is within time limit
- Takeoff and Landing employ waypoints
  - Evaluating waypoints done using lookahead
- Takeoff time sampling also employed
  - Takeoff time evaluating also done using lookahead



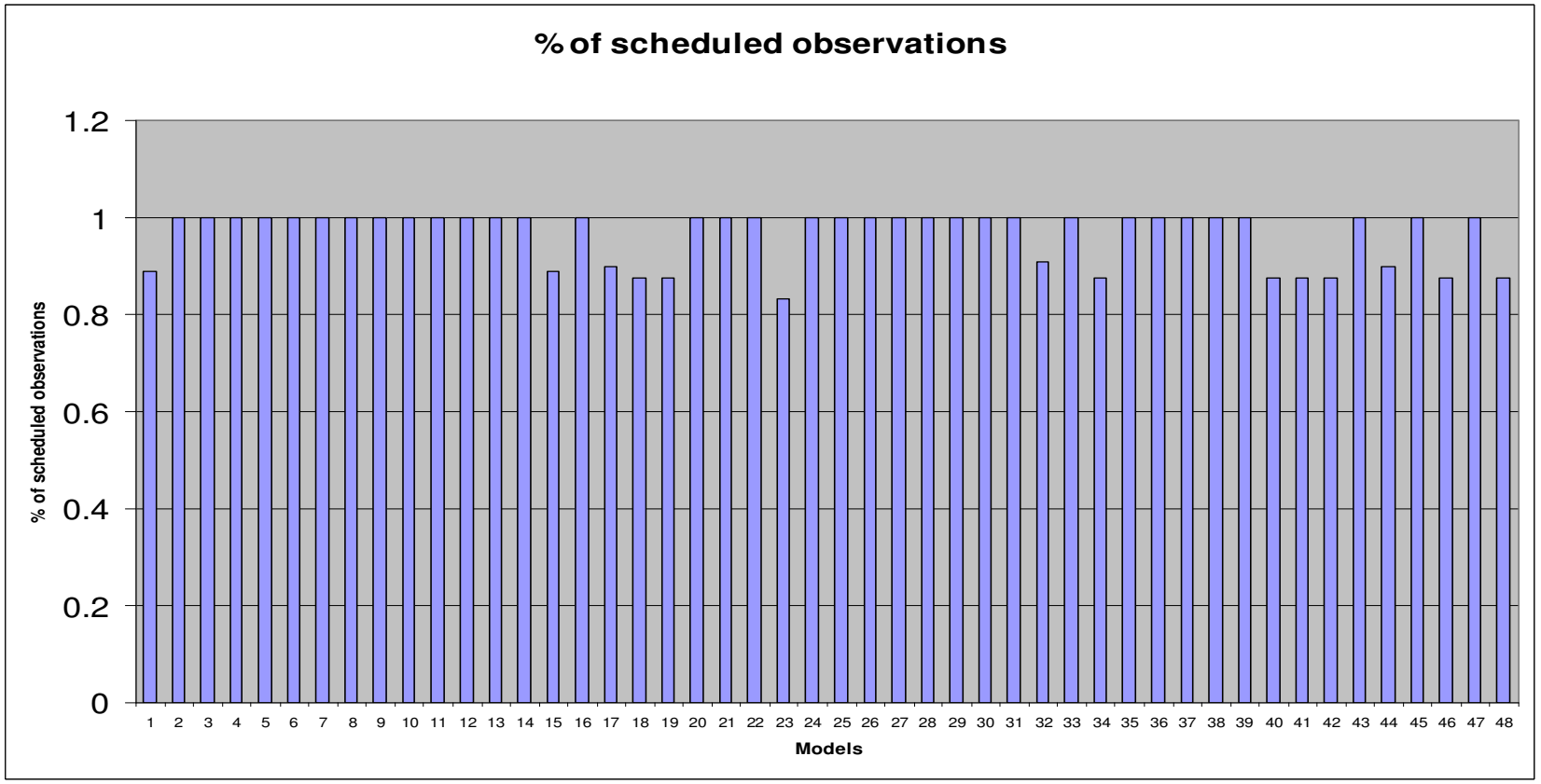
Nominal Forward Planning Algorithm

- Initial testing on a small test suite
  - Lookahead depth strongly affects performance
  - All heuristic features needed for good performance
  - Greedy selection is better than random selection
  - Synergies between feature settings
    - E.g. for low lookahead depth, more noise is better
    - Implies heuristic is weaker
- Nominal algorithm
  - Lookahead depth 4
  - Feature weights
    - Lookahead: H=D=T=P=0.25
    - Observation selection: R=E=0.5
  - Greedy selection for both lookahead and observation selection (I.e. no stochastic selection)
  - 5 Start time samples

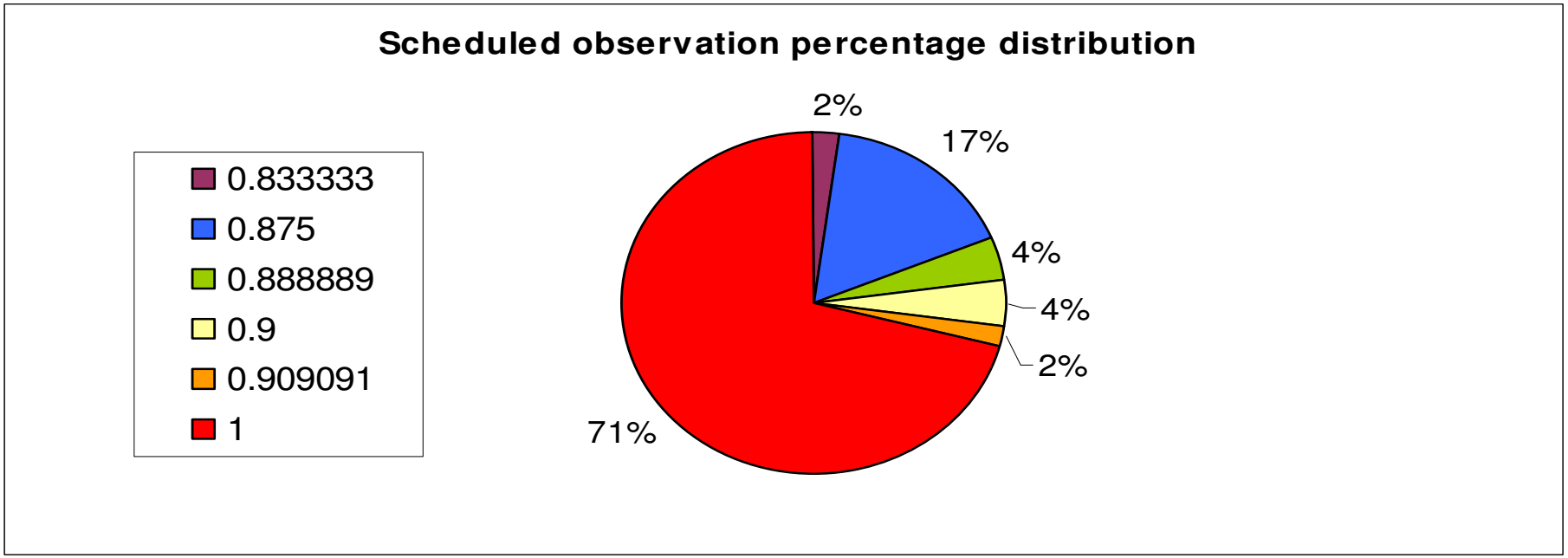
Testing Forward Search with Heuristics

- Test problems
  - Survey of flights on the Kuiper Airborne Observatory
    - 35 flights from Moffett Field
    - 4 flights from Moffett to Hawaii
    - 5 Flights from New Zealand
    - 4 Flights from Hawaii
    - Flights span the seasons
- Details
  - Know in advance that all requests can be scheduled
  - Also know flight duration
    - Affected by winds, restricted airspace
  - Allowed 10% more time for flight duration
  - Legal takeoff times extended by 30 minutes before actual takeoff, 30 minutes after actual landing time
  - Assume all priorities are identical
- Goal: to demonstrate effectiveness of automated approach

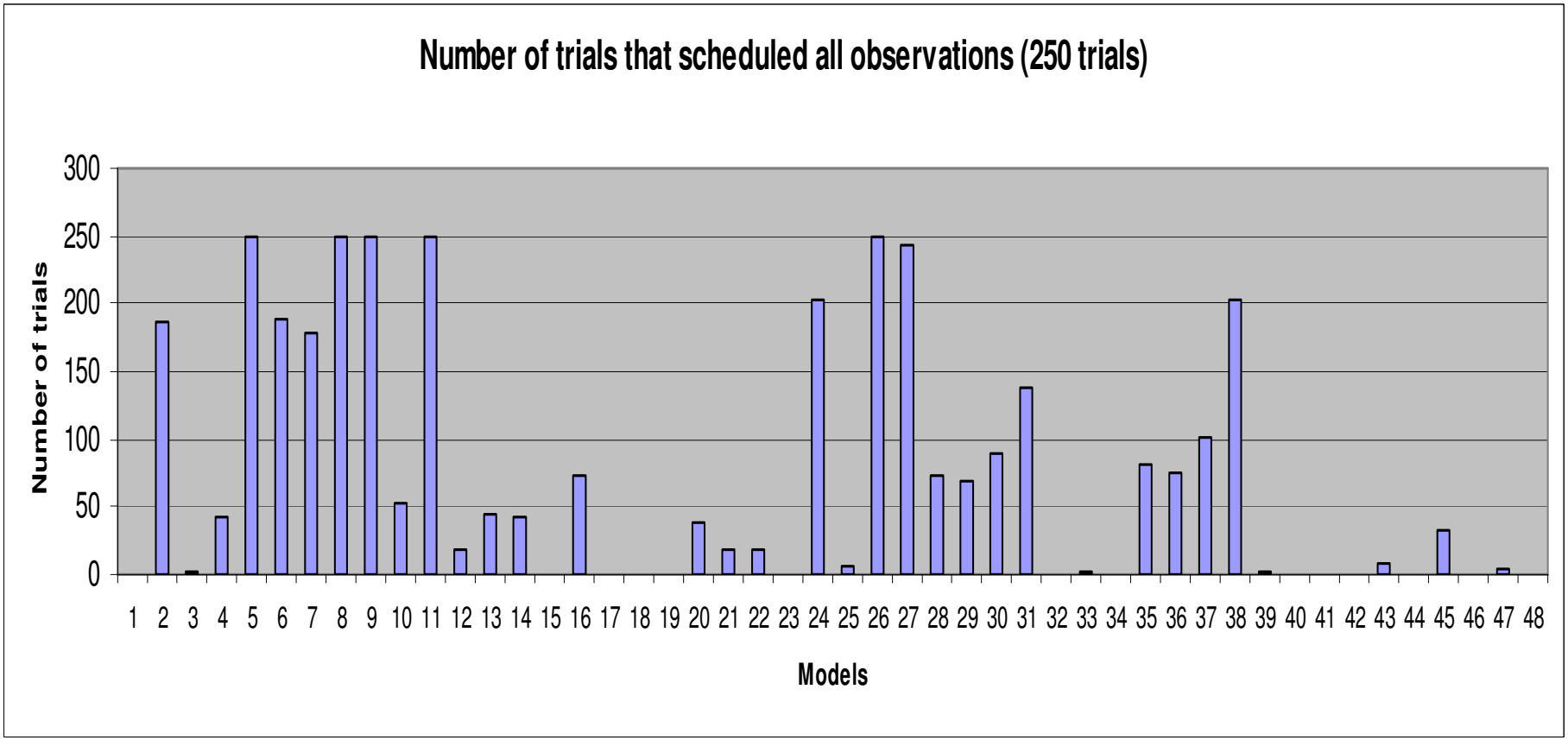
Results I: Success rate



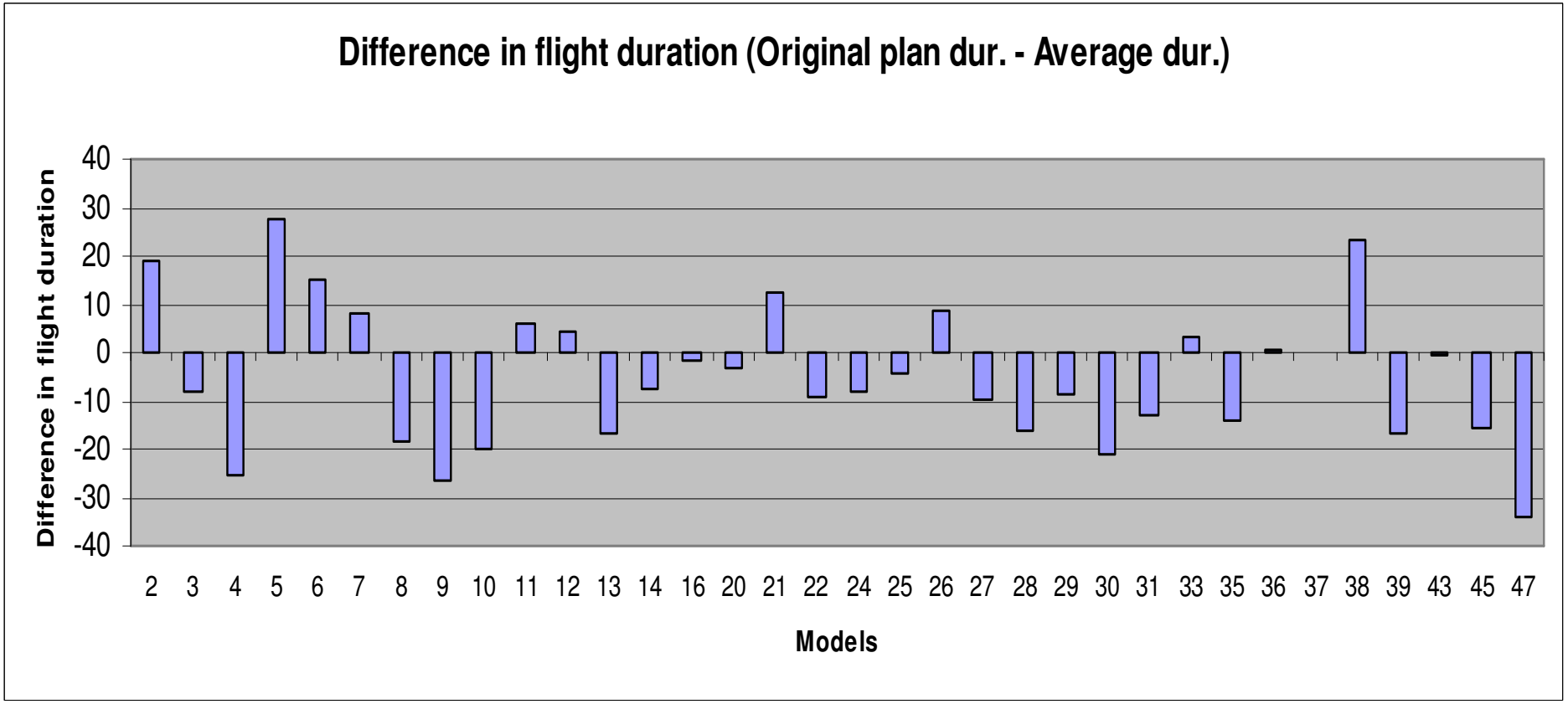
Results I: Success rate



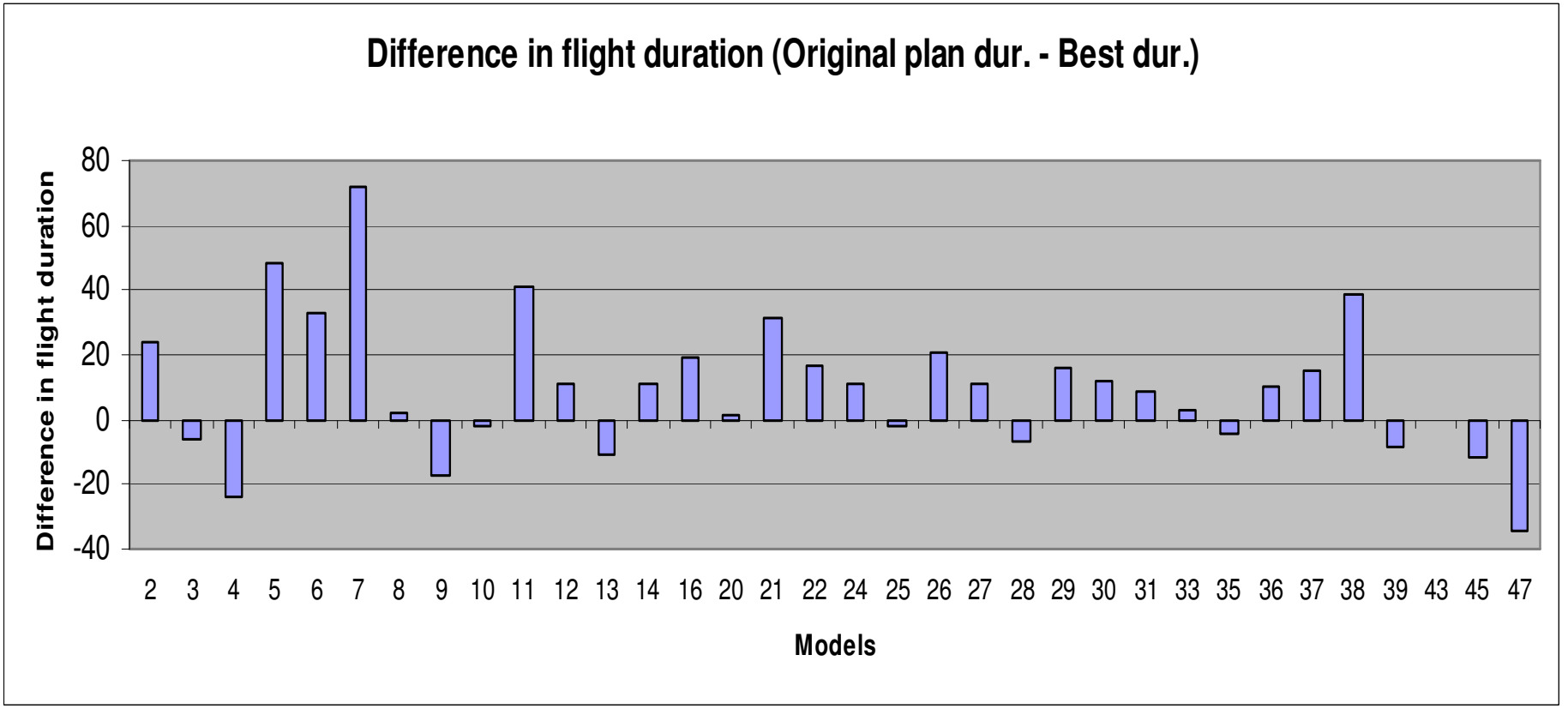
Results II: Robustness



Results III: Efficiency



Results III: Efficiency



Continuing work

- Model fidelity
  - Vary observation priority
    - Distinguish between science, calibration and setup steps
  - Winds
  - Restricted airspace
    - Strongly affects Moffett Field flights
  - Measure activity duration in seconds
  - Flight duration constraint
    - Add more sophisticated fuel consumption model
  - Altitude profile for flight and altitude constraints on obs.
  - Extend problem scope to planning flight sequences
- Algorithm enhancements
  - "Squeaky Wheel" search
  - Path planning component to handle restricted zones
  - Multi-start learning to intelligently set parameters

Problem:

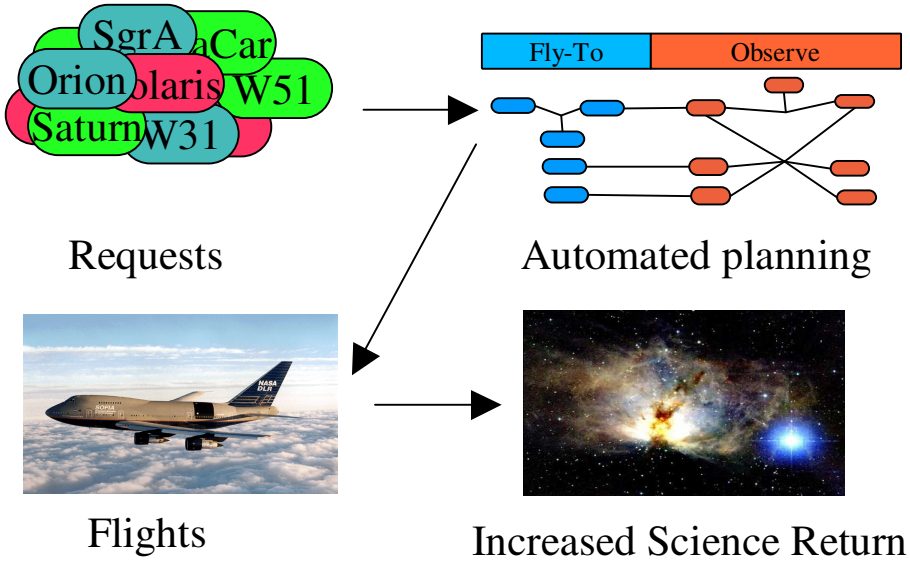
The SOFIA General Investigator (GI) Program will require assembling flight plans to support individual observation requests. The manual flight planning approach used for the Kuiper Airborne Observatory (KAO) cannot meet the expected demand.

Objectives:

1. Identify and implement domain specific constraints required to represent the flight planning domain.
2. Model the problem of planning a single flight as an optimal planning problem.
3. Build planners and heuristics to solve the resulting problem.

Key Innovation:

1. Use constraint-based planning to solve complex constrained optimization problem.
2. Demonstrate planning with continuous quantities.



NASA Relevance:

Direct project relevance (expect to influence SOFIA GI program and SOFIA operations; mission co-funding in FY02.)

SOFIA problem related to other problems in astronomy, data collection by automated robots such as rovers and submarines.

Accomplishments:

Model reviewed by SOFIA experts.

Search algorithm selected (HBSS with progression planning).

Heuristics designed and evaluated.

Schedule:

Enhance model fidelity - October 2002

Revise planning algorithm and heuristics - November 2002

Evaluate search algorithms - January 2003

Extend to handle sequences of flights - June 2003

Integrate with mission software - throughout 2003